USE OF MULTI-LAYER THIN FILMS AS STRESS SENSORS

Field of the Invention

The present invention relates to Tunneling MagnetoResistive (TMR) devices in conjunction with micromachined beams to measure stresses with high sensitivity, and methods of making and using the same.

Background of the Invention

Historically, fingerprint image-capture devices have used optical-based sensors or capacitance-based sensors. With reference to the specific example of a fingerprint, optical sensors use a light source, lenses and a prism to image the "ridges" and valleys on the fingerprint, based on differences in the reflected light from the features. The conventional capacitance sensor uses semiconductor type processing to fabricate a two-dimensional array of capacitors. The individual sensors form one plate of the parallel plate capacitor, while the finger itself, when placed on the array, acts as the second plate. Upon contact with the array of sensors, the individual distance from each sensor to the skin is measured using capacitive techniques. The difference in distance to skin at the ridges and valleys of a fingerprint provide the means to replicate the fingerprint. An example of the use of capacitive sensors to measure the spacing is shown in Figure 1A and 1B.

Both the above techniques fundamentally measure the spacing between the fingerprint features, and the sensor. The measurement of spacing is inherently subject to several distortion effects: since the height difference between the ridges and valleys is only of the order of 50 microns, any parameter which affects the spacing between the finger and the sensor will affect the measurement. For example, both types of sensors are very sensitive to the thickness of the protective coating. They are also sensitive to oils or grease on the finger, and the presence or

absence of moisture on the finger. In addition, most of these sensors are adversely affected by ambient temperature at the time of sensing, as well as electrostatic discharge (ESD). Under very hot or very cold conditions, the capacitive sensor can provide erroneous readings. ESD can altogether destroy a sensor. The combined effect of all these variables results in a very distorted image, if any, of the fingerprint, as shown in Figure 1C.

As a result of the above drawbacks to spacing based reproduction of fingerprints, it would be very useful to be able to use the difference in pressure exerted by the ridges and valleys of a fingerprint on a sensor to replicate the fingerprint image. In principle, a pressure-based fingerprint sensor would be impervious to the drawbacks listed above, such as wet or dry conditions on the fingertip, presence of oil or grease on the fingertip, thickness of protective coatings, etc., providing a "digital" response, depending on whether the sensor experiences a ridge or not. This situation is illustrated in Figure 1D and 1E, where the pressure sensor can highlight only the ridges, which are the lines of interest in a fingerprint. However, due to a variety of factors, including the very low sensitivity and inability to provide the required resolution, pressure based sensors have not been deployed for the replication of fingerprints.

Improvements in pressure sensors are described in U.S. Patent Application No. 09/500,706 entitled "Magnetoresistive Semiconductor Pressure Sensor and Fingerprint/ Verification Sensors Using the Same" and U.S. Patent Application No. 09/502,406 entitled "Use of Multi-Layer Thin Films as Stress Sensors, Appln., both assigned to the same assignee as the present invention. These applications describe many different improved aspects of pressure sensors, including sensors based upon magnetostriction and the GMR effect.

While the above applications provide many advantages, improvements that can result in greater sensitivity, less power consumption and lower thermal build-up are nonetheless desirable.

The present invention, as described below, described such a device, which, as one of it aspects, operates using the Tunneling MagnetoResistive (TMR) effect. The TMR effect was discovered relatively recently in the mid 1980's by Julliere et al. Since then researchers in the area of random access and flash semiconductor memories have explored the TMR principle to enhance the utility of such devices. This research, however, has been limited to these areas, and has not been reported as having usefulness in the context of fingerprint and pressure sensing applications.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a TMR sensor for the detection of pressure or stress.

It is an object of the present invention to provide a TMR sensor that includes two ferromagnetic layers separated by an electron-tunneling barrier, with electrical Current flowing Perpendicular to the Plane of the layers (CPP).

It is another object of the current invention to magnetically pin one ferromagnetic layer while allowing the other ferromagnetic layer to rotate freely under the action of an externally applied stress.

It is another object of the current invention to reduce the magnetic moment of the free ferromagnetic layer by forming a composite trilayer stack containing a ferromagnetic layer, a spacer layer, and another antiferromagnetically-coupled ferromagnetic layer, referred to together as the synthetic free layer (SyFL).

It is another object of the current invention to reduce the magnetic moment of the pinned ferromagnetic layer by forming a composite trilayer stack containing a ferromagnetic layer, a

spacer layer, and another antiferromagnetically-coupled ferromagnetic layer, referred to together as the synthetic pinned layer (SyPL).

It is a further object of the present invention to provide a TMR sensor capable of sensing both compressive stress and tension.

It a further object of the present invention is to provide a TMR sensor that is protected from Electro-Static Discharge (ESD).

It is a further object of the present invention to provide a TMR sensor that can be adapted to have substantial independence from temperature shifts.

Another object of the invention is to provide a TMR sensor that is suitable for use in fingerprint identification and verification.

Another object of the invention is to provide a TMR sensor that is suitable for use in fingerprint identification and verification and that is less sensitive to adverse conditions such as extreme temperatures and skin oils and grease.

The present invention fulfills these and other objects of the present invention, by providing a pressure sensing device that includes at least one lithographically patterned TMR sensor, but preferably an array of TMR sensors, with each TMR sensor having an insulating spacer layer interposed between a free and a pinned ferromagnetic layer. In an unbiased state, the magnetization vectors of the ferromagnetic layers are preferably parallel to each other, but can also be antiparallel to each other and still remain stable with respect to each other. Upon application of a small voltage, the magnetization vectors remain unchanged. Upon application of stress, the magnetization vector of the free layer will rotate away from parallelism with the pinned layer, thus causing a corresponding and proportionally related change in the resistance of

the magnetic material of the sensor. This change in resistance can be sensed and used to calculate the stress applied thereto.

While the above provides an overview of the invention, there exist numerous other significant aspects and advantages that will become apparent in the discussion provided hereinafter. In this regard, for instance, reference to a free layer magnetization can interchange-ably reference the net moment of a synthetic free layer stack. The same holds for the pinned layer, which can just as well be replaced with a synthetic pinned layer stack.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other objectives, features, and advantages of the present invention are further described in the detailed description which follows, with reference to the drawings by way of non-limiting exemplary embodiments of the present invention, wherein like reference numerals represent similar parts of the present invention throughout several views and wherein:

FIGS. 1A – 1E are side views of a fingertip on a prior art capacitive sensor, and on a potential pressure sensor according to the present invention which illustrate the use of spacing versus pressure for replicating the fingerprint, and the distortion associated with the prior art.

FIG. 2 is a schematic view of a conventional TMR multi-layer stack, using alternating ferromagnetic layers separated by a non-magnetic insulating spacer.

FIG. 3 is a graph illustrating the resistance response of a GMR/TMR multi-layer stack to changes in relative angle between the alternating ferromagnetic layers.

FIG. 4 is a schematic of the cross-section of a TMR sensor stack according to a preferred embodiment of the present invention.

FIGS. 5A-5B show the magnetization configuration of the free and pinned layer net moments before and after the application of external uniaxial stress along the length direction. In

5A, the magnetizations are shown parallel to each other, providing low resistance to current, and in 5B, the magnetizations are shown at 90 degrees to each other, providing a higher resistance to current flow.

FIG. 6 shows the computation of TMR% as a function of $H_{k,eff}$ according to the present invention.

FIG. 7 shows the computation of TMR% as a function of applied stress in dynes/cm^2 according to the present invention.

FIG. 8 shows the resulting Gauge Factor as a function of applied stress in dynes/cm^2 according to the present invention.

FIG. 9 shows the ability to tailor sensitivity of the device by means of stiffness change in the underlying beam substrate according to the present invention.

FIG. 10 illustrates a beam or diaphragm substrate on which a TMR sensor is deposited and patterned in accordance with the invention.

FIG. 11 illustrates a two dimensional array of beams or diaphragms employing TMR devices such as those illustrated in FIG. 4 and FIG. 5 for use as pressure sensors in accordance with the invention.

FIG. 12 illustrates the use of a conductive layer separated by an insulating spacer from the sensor on the beam, according to the present invention.

FIG. 13 illustrates an example of circuitry for performing electronic measurement in a two dimensional array of pressure sensors employing TMR sensor such as that illustrated in FIG. 10 in accordance with the invention.

FIGS. 14A-E illustrate a method for fabricating a beam or diaphragm which would employ a TMR device such as that illustrated in FIG. 4 and FIG. 5 for the purpose of pressure sensing in accordance with the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The working principle of TMR has certain similarities to that of GMR, since in both TMR sensors (as described herein) and GMR sensors, a change in applied pressure will cause a rotation of the magnetization associated with the device, and a corresponding change in resistance, which can be sensed. Further, in both devices, there is a stack of layers, in which the innermost and outermost layers are made of ferromagnetic materials. Despite those similarities, implementation of a TMR device is very different from implementation of a GMR device. In particular, this is due to the fact that the layer between the inner and outer ferromagnetic layers is an insulating, rather than a conducting material, and the electrical current flows perpendicular to the plane of the layers, rather than in the plane of the layers.

As a result of these differences, the following observations have been noted by the present inventors, which lead to the conclusion that a TMR device can have advantages to GMR device when both are used as a sensitive strain gauge.

Firstly, due to the low resistance of a GMR device, electrical currents in the milliampere range are required for generating sufficient output voltage. For example, for a typical GMR sensor with 100 ohm resistance and 5% usable GMR effect, a 2 mA current will produce a voltage output of only 10 mV, but a 4 mA current will produce a more measurable output of 20 mV. This quadruples the power requirement of the device. By comparison, a TMR device with a resistance of 10^5 ohms and 10% usable TMR effect will produce the same output voltage of 20 mV with only 2 μA current flowing.

Secondly, the I^2R heating effect is relatively high for a spin valve sensor that uses the GMR effect, since it uses more current (in the mA range). In the example cited in the paragraph above, the GMR sensor will dissipate 1.6 mW, whereas the TMR sensor will dissipate 3 orders of magnitude less power. Thus, the I^2R heating effect is an important limitation in applications that need a dense array of sensors, such as in fingerprint sensors, and also in situations where temperature control is critical for accurate calibration and reading of strain. With the GMR sensor, the temperature of the sensor during operation is a compound effect of both ambient temperature variation and temperature rise due to this intrinsic heat dissipation. Separating these effects involve additional features that add cost, which are eliminated with TMR sensors.

Thirdly, and specifically in situations such as fingerprint sensors where large sensor arrays are used, the mA current per sensor requirement causes another undesirable side effect. This is the exceedingly high *total* current flowing through all the sensors in the array. For a 256 x 256 array, this could quite easily exceed 1 Ampere. The external circuits have to be made robust to deal with such high currents, which will again increase the total cost to the user, or make the product cost-ineffective.

Fourthly, the absolute value of the magnetoresistive effect is limited for the GMR spin valve sensor to about 15%. For a tunneling spin valve sensor, by comparison, the magnetoresistive effect can be as high as 40%. Gage factors can thus be much higher for TMR sensors, as described further hereinafter.

Fig. 2 shows the basic structure of a TMR device, in which there are alternating ferromagnetic layers 12, made from elements such as Cobalt, Iron or Nickel, are separated by a nonmagnetic insulator layer 14, such as aluminum oxide to form a sensor 10. When an electrical current is imposed across the thickness direction of the sensor (Current Perpendicular to Plane or

CPP direction), the electrical resistance of the multi-layer stack of films varies as the relative angle between the magnetizations of the individual ferromagnetic layers, as shown in Figure 3. The resistance is a minimum when the magnetization vectors between the neighboring ferromagnetic layers are parallel to each other, and is maximum when the two vectors are antiparallel to each other (at 180^0), as shown in Figure 2 and Figure 3.

The change in electrical resistance of a TMR multi-layer stack for full rotation of the magnetization vector from a parallel to an antiparallel state can be anywhere from 2% to 40%, which are approximately twice that of GMR values. Accordingly, one aspect of the present invention is based upon rotating the magnetization of some layers in a TMR multi-layer stack under the application of stress in order to provide a greater sensitivity pressure sensor.

Before describing the initial preferred embodiment in detail, an overview of the concepts that are used by the present invention will be first provided. Subsequently, the preferred embodiments and alternative embodiments will be discussed.

The rotation of the magnetization vector of a soft ferromagnetic layer that comes about from the magnetoelastic driving force is proportional to the product of the stress and the magnetostriction. The sensors of the present invention based upon this concept are multi-layer thin film stacks, which are deposited onto the substrate to be monitored, and photolitho-graphically patterned to a certain aspect ratio, defined as the length/width ratio. A uniaxial compressive or tensile stress in bending, acting upon the flexible beam substrate and therefore upon the sensor, preferably along its length, produces a rotation of the magnetization vector of the free layer or SyFL layer, even under the absence of an external magnetic field. The free layer's initial magnetic orientation prior to stress application is orthogonal to the stress direction, and preferably parallel to the magnetic orientation of the second ferromagnetic pinned layer or

SyPL layer. A requirement for this magnetization rotation is the sensor's property of magnetostriction, which must be non-zero ($>+10^{-7}$ or $<-10^{-7}$), preferably +/- 10^{-5} and whose sign must be appropriate for the sign of the stress. The rotation of the magnetization in turn produces a change in the resistivity of the magnetic material, and, in the presence of voltage applied to the device, causes a corresponding change in the current flow.

This invention describes a preferred embodiment that uses an antiferromagnetic layer to fix the magnetizations of the pinned ferromagnetic layer. Specifically, as shown in Figure 4, the preferred embodiment includes, in order from the substrate 400, the underlayer 410, the (synthetic) free layer 420, the insulating barrier layer 430, the (synthetic) pinned layer 440, the antiferromagnetic pinning layer 450, and the capping protective layer 460. Each ferromagnetic layer 420 and 440 can be a single or multiple layers, and each of the ferromagnetic layers 420 and 440 yield non-zero magnetostriction.

Figure 4 illustrates an exemplary five layer synthetic ferromagnet structure composed of NiFe 420-1, CoFe 420-2, Ru 420-3, CoFe 420-4 and NiFe 420-5. Of course, the materials used in the composite can change in type, order, number and other variables to make up the synthetic free layer 420, and NiFe 440-1, CoFe 440-2, Ru 440-3, CoFe 440-4 and NiFe 440-5 make up the preferred synthetic pinned layer 440, again with the variations of the type noted above being contemplated. NiFeCo, Co or other ferromagnetic materials can also be used for the ferromagnetic layers. The thickness of each ferromagnetic layer is typically within the range of 0.1 – 50 nm. The antiferrogmagnetic pinning layer can be made of, for example, CrMnPd. The capping layer can be made of, for example, Tantalum.

The barrier layer 430 provides for a small ferromagnetic coupling H_{ilc} between the pinned ferromagnetic layer 440 and the free ferromagnetic layer 420, which in the case of the preferred

embodiment is such that the magnetization vectors of the individual layers on either side of the barrier layer 430 are pointed in the same direction and orthogonal to the length of the sensor, as shown in Figure 5A. Barrier layer 430 is made of a non-magnetic, electrically insulating material, such as Aluminum Oxide. In the preferred embodiment, the thickness of the barrier layer 430 is within the range of 0.1 to 10 nm.

In the quiescent, zero stress state of the device, the resistance of the sensor is preferably at the extreme value of minimum resistance (parallel net magnetization vectors for free and pinned layers, fig. 5A) as shown in Figure 3, left hand side of the graph. The resistance of the sensor is determined specifically by the relative angle between the magnetization vectors of the individual ferromagnetic layers 420 and 440 on either side of the barrier layer 430. Parallelism is described by a zero angle, antiparallelism by 180 degrees, etc.

Under application of stress, for an appropriate combination of sign of magnetostriction and sign of stress along the length of the sensor, the free layer 420 will rotate towards the length direction, as shown by Figure 5B. As it rotates, the angle between the moment (or magnetization) vectors of the free layer 420 and pinned layer 440 increases from zero, and the resistance of the device increases. One can thus use this resistance change as a measure of the stress. In the fully saturated state, the moments of the layers 420 and 440 are 90 degrees to each other, and the resistance of the sensor is at the midpoint.

That a useful resistance change can be achieved as a result of the magnetization of the sensor films can be shown with reference to an exemplary sensor having an aspect ratio of 1.5. Where:

H_{ilc}: the interlayer coupling field, which can be controlled to approximately 2-5 Oe, in the +y (width) direction, ferromagnetic in nature due to interfacial roughness.

$H_{k,i}$: intrinsic growth anisotropy, in the +/- y direction, induced at film growth.

$H_{d,f}$: Demagnetization field in the free layer due to charges accumulating at edges. This follows the magnetization and is kept to a minimum (designed out) by utilizing a synthetic free layer with low or no net moment.

$H_{d,p}$: Demagnetization field in the pinned layer due to charges accumulating at edges. This follows the magnetization and is kept to a minimum (designed out) by utilizing a synthetic pinned layer with low or no net moment.

$H_{k,\sigma}$: Stress-induced anisotropy in the +/- x direction, due to the application of stress.

$H_{k,eff}$: Effective H_k in the applied stress (x) direction whose magnitude is equal to $H_{k,\sigma}$-$H_{k,i}$. i.e.

$$H_{k,eff} = H_{k,\sigma} - H_{k,i} \qquad \ldots\ldots 1$$

The output of the sensor is proportional to the average value of a cosine function $\langle\cos\rangle$, which is defined as:

$$\langle\cos\rangle = (1 - \langle\cos(\theta_p - \theta_f)\rangle)/2 \qquad \ldots\ldots 2$$

$\langle\cos(\theta_p - \theta_f)\rangle$ provides the average value of the cosine of the angle between the magnetizations of the pinned and free layers across the sensor. This varies with applied stress via the property of magnetostriction. The average cosine function can be determined as a function of $H_{k,eff}$ by deriving and solving the equations for the minimization of magnetic free energy. The useful TMR% as a function of $H_{k,eff}$ can then be obtained using the following basic relationship of TMR% to the cosine function:

$$TMR\% = TMR\%_{max} \times (\langle\cos\rangle_f - \langle\cos\rangle_i) \qquad \ldots\ldots 3$$

The subscripts f and i are for final and initial states, i.e. stressed and unstressed states.

In equation 3, $\langle \cos \rangle_f$ is a function of stress, or more precisely, of the effective anisotropy, $H_{k,eff}$., which is the difference between the stress-induced anisotropy and intrinsic anisotropy. The TMR% as a function of $H_{k,eff}$ is shown graphically in Figure 6. Note the rapid increase of TMR% with small stress and the asymptotic saturation at higher values. This is a desirable property, since it provides a high sensitivity to the detection of stress, and a "digital" response. $TMR\%_{max}$ has been assumed as 25% and the maximum percent resistance change obtainable is $0.5TMR\%_{max}$, due to the 90 degree maximum rotation of the free layer.

The equation that describes the relationship of $H_{k,\sigma}$ to stress is:

$$H_{k,\sigma} = 3 \text{ X } \lambda \text{ X } \sigma / M_s \qquad \ldots\ldots 4$$

Where λ and σ are magnetostriction and stress, and M_s is the saturation magnetization of the free layer.

The TMR% can be plotted as a function of stress using equation 1 and 4, to generate Figure 7.

The rapid rise of TMR% with low stress values (low 1e8 range, in dyn/cm2) shows the sensitivity of the sensor more clearly.

Gage factor, which provides a quantitative measure of this sensitivity, is defined as: dR/ε. It can also be written as $dR.E/\sigma$, where ε is the strain, E the modulus of elasticity, and dR the change in resistance as a percentage. i.e.

$$g.f. = dR.E/\sigma \qquad \ldots\ldots 5$$

Substituting the values into equation 5, Figure 8 can be generated, which shows the gage factor as a function of stress. The maximum gage factor occurs at very low stress values, which again confirms the high sensitivity of this sensor. Conventional sensors for pressure detection

provide a maximum gage factor in the 75 to 150 range, far below the value of 900 for this TMR sensor.

The sensor can be grown on a beam or membrane, whose mechanical properties determine the magnitude of the strain and thus the stress applied to the sensor. Figure 9 shows how the gage factor curve can be tailored by the mechanical property of the beams, in this instance two cantilevers with different stiffness constants. Two cantilever substrates are used with different stiffness constants, causing the Gauge Factor curve of each to shift with respect to the applied stress. The stiffness of the cantilevers can be varied by changing their length, width and thickness.

Pressure sensor application of the TMR Sensor

In accordance with an aspect of the invention, a multi-layer stack 1010 is the basis for a novel stress or pressure sensor, which can be used, for example, for fingerprint sensing. In order to use it, the underlying base structure for the TMR sensor 1010 is fabricated as a suspended bridge, a cantilevered beam 1004 or a similar kind of membrane that is supported over a cavity 1008 that is formed in a bulk substrate and allows for deformation of the cantilevered beam 1004, as shown in Figure 10. An example of a method of fabricating this is described in more detail below. A TMR stack 1010 comprising the two ferromagnetic layers, the non-magnetic insulating spacer layer and the underlayer and capping layers are deposited on deformable beam 1004, and leads 1012 are connected thereto to apply a voltage across it and to measure the resulting spin-polarized tunneling current and resistance. It should be apparent that the support structure for TMR layer 1010 can be a variety of different structures other than the beam 1004 of this example, such as a sealed membrane over an enclosure, or any other form that may be

suitable for detecting deflection and stress. An example would be where the TMR sensor is located under the beam, and thus subjected to compressive rather than tensile stresses.

Under the application of a force on the beam 1004, it deflects. Note that in this configuration of the beam, the stress direction needs to be either unidirectional or if bidirectional, needs to be different along the two principal axes. If the length of the beam is "L", the width "W", and the thickness "t", for a load "4Q" acting on a length L/4 at the end, the maximum tensile stress at the base of the beam where the sensor is located is approximately given by:

$$\sigma_{max} = Mt/2I = (7/16)QL^2t/I \qquad \ldots\ldots 6$$

where M is the bending moment, and I is the moment of inertia about the vertical axis.

The maximum stress and strain occur on the surface of the beam. Since the multi-layer stack 1010 is located on the surface of the beam 1004, and is a very thin set of films, for calculation and illustration purposes, one can assume that the TMR element is subjected to the maximum stress and strain.

Under these conditions, the multi-layer stack is subjected to the maximum tensile stress on the beam surface, as the beam bends in response to applied pressure. The magnetostriction of the device causes the resistance of the element to change depending on the sign of the applied stress, as described earlier. In this way, by measuring the resistance prior to and during the application of the stress, the difference in resistance gives a good indication of the magnitude of the stress. If the system is calibrated, this can give an idea of the absolute stress as well as just the presence of a pressure point.

In accordance with an aspect of the invention, the sensitivity of the device as described above exceeds the sensitivity of a capacitance-based sensor or a piezoresistive sensor. As a result, considerable miniaturization can be realized with TMR sensor 1010. With conventional

fabrication methods, the TMR element can be made as small as 4 microns long and 3 microns wide while maintaining considerable sensitivity. It is desirable to make the beam as long as possible within the constraints of the product, because sensitivity only improves with the length of the beam.

In order to achieve the maximum sensitivity of the sensor to an applied stress, it is appropriate to choose an alloy and deposition conditions that would ensure a maximum ΔR/R response from the material, as well as a maximum magnetostriction coefficient.

A tunneling magnetoresistive pressure sensor 1102 (that can be used for fingerprint verification/identification, for example) employing TMR sensors 1110 as described above will now be described in detail with reference to Figure 11. Several sensors 1110 as described above are placed in an array 1106 of m rows by n columns on a substrate 1104, with a very fine pitch, and connected to electrodes 1108. Because the sensors can be made as small as 4 microns in length, the lateral resolution can easily satisfy requirements which are typically set for fingerprint applications, such as 500 dots per inch, as well as even more stringent requirements. For example, when a finger is placed on the array, the ridges on the fingers (which are spaced at about 400 – 500 microns, and are therefore considerably wider than the sensor pitch in the array), apply a force on the sensors that they come in contact with. The sensors that fall between the ridges experience little to no stress. In this way, one can generate a map of the contact points or the ridges on the fingerprint, and get an accurate reproduction of the fingerprint. However, in practice, the sensor length and pitch can be made greater than 5 microns, since such a good resolution is typically not required for a fingerprint image. Moreover, as the sensor pitch decreases, the processing time for the image increases, since the number of sensors in the image increases as well. The length of the multi-layer stack is typically in the range of 2-200 microns,

and the width is in the range of 0.1 – 100 microns. For a fingerprint image capture application, the sensor dimensions are preferably 0.5– 5 micron wide and 5-10 micron long.

In order to protect the TMR sensor during its use as a fingerprint sensor, different schemes may be used. For ESD protection, Fig. 12 shows a fixed beam 1204 disposed over a cavity 1202, with TMR stack 1210 formed in this example on the center of the beam 1204. A layer of insulating material 1212 then coated on top of the GMR stack 1210, and then another layer 1214 of a conductive metal (such as Titanium, copper, etc.) is deposited, whose purpose is to bleed off transient charges caused by ESD and protect the sensor from ESD damage. This conductive film 1214 needs to be grounded, so that the charges from the transient voltage spikes can be bled to ground. This is illustrated in Figure 12, with grounding leads 1216A and 1216B shown from the conductive layer in order to dissipate ESD charges to ground that is within the substrate. Another embodiment for ESD protection puts the sensor on the underside of the deflecting beam or membrane, such that the beam material and thickness act as a protective shield against ESD.

Secondly, to protect the TMR stack from mechanical abrasion or small impact, a hard coating can be deposited both above and below the conductive ESD protection layer. The thicknesses of all these layers would be in the range of 0.001μm – 10μm. The material used for the mechanically protective coatings could be a material such as carbon based material, such as "diamond like carbon" or silicon carbide, for example. These materials can also be tailored to have surface energies such that undesired deposits, such as debris or oils from the finger, are prevented from adhering to the coating.

An example of electronic circuitry and a method that can be used to probe an array of sensors either individually or as a group is shown in Figure 13. It includes a decoder 1302, a

multiplexer 1304, and amplifier 1306, and A/D converter 1308. The techniques for providing such electronic circuitry and method according to this example are well known and detailed descriptions thereof are not necessary for an understanding of the present invention. It is noted that there are several different methods of scanning and addressing the array. One approach is shown in Figure 13, which employs transistors or diodes to isolate each element of the array during addressing of the array. An alternate cell addressing method is described in U.S. Patent Application No. 09/571,765, filed May 16, 2000 entitled "Method and Apparatus for Pressure Sensing", and does not require the use of transistors or diodes to address each element of the array.

In accordance with an aspect of a method of fingerprint identification/verification in accordance with the invention, a baseline is first established that determines whether there is a stress on a particular sensor with no finger on the sensor, wherein the "quiescent" resistance of each element of the array is measured. Then the readings are repeated with the finger on the sensor, and the difference in voltages/currents between the "quiescent, unstressed" state and the "stressed" state is calculated to determine the fingerprint pattern. The baseline can desirably be established either immediately prior to or immediately following the imaging of the fingerprint. While one method of scanning, providing power to each element, selectively addressing each element either using transistors or diodes, as shown in Figure 13, or the cell addressing method described in U.S. Patent Application No. 09/571,765, filed May 16, 2000 entitled "Method and Apparatus for Pressure Sensing", conversion of values from analog to digital, etc are well known.

An advantage of the method of establishing a baseline in this invention is that it always establishes a reference value, which eliminates the effect of ambient temperature, humidity,

stress, etc. The prior art, using capacitive or optical means are unable to obtain such a reference each time a measurement is taken, because they depend on the presence of a finger to obtain a reading each time. Even though the resistance of the sensor changes with temperature, this effect can be automatically compensated for by establishing a reference value, either immediately prior to or immediately following the fingerprint imaging, as noted above.

It should be apparent to those skilled in the art that since the TMR sensor's output depends on a number of factors, it can be used in a variety of alternative ways in this and other embodiments other than for fingerprint identification/verification.

An example of a method for manufacturing a magnetoresistive sensor in accordance with the invention will now be described with reference to Figure 14. As shown in Figure 14A, a layer of silicon nitride 1404 is first deposited on a silicon substrate 1402, then a layer of polysilicon 1406, followed by another layer of silicon nitride 1408. Then the pattern of the beam is etched using photolithography by depositing a layer of photoresist 1410 as shown in Figure. 14B , and etching through at least the top two layers of silicon nitride and polysilicon as shown in Figure 14C. This is followed by preferentially etching out the second layer of polysilicon underneath the silicon nitride in the beam portion 1412, thus forming a simply suspended beam 1412 of the upper layer of silicon nitride as shown in Figure 14D.

Alternatively, using similar techniques as are known in the art, a thin silicon beam or membrane is made by starting from a silicon wafer using conventional processing means as have been described elsewhere in the literature. This is typically done either by etching from the back side using anisotropic etchants, or using single sided wafer processing, by first doping the wafer with n-type doping elements (arsenic), covering with a layer of epitaxial silicon, then etching using a chlorine gas plasma to preferentially etch the N+ region. The preferential etching of the

N+ region under the top layer of epitaxial silicon leaves the upper layer suspended as a beam, supported on either side.

It should be noted that even though the manufacturing descriptions above are for the processing of silicon, one can use other materials to achieve the same purpose as well. For example, one could use a substrate of Aluminum, coat it with a layer of insulating alumina (using thin film deposition techniques that are well known), sputter another layer of metal (such as aluminum, titanium, copper, etc.). One can now perform photolithography and use dry etching techniques (such as ion milling) to etch down to the underlying layer of aluminum, and then use etchants that are selective to alumina to etch out the underlying alumina layer. In this way, a "bridge" structure of aluminum or other metal can be formed as well.

Once the beam is formed, a series of thin films is deposited using thin film techniques (typically a cluster tool), representing the magnetoresistive "stack". This series of materials comprises a tantalum layer (the underlayer), the free layer (or synthetic free layer stack SyFL), the barrier layer of aluminum oxide, the pinned layer (or synthetic pinned layer stack SyPL), the antiferromagnet layer, and finally the capping layer. This stack of thin films is deposited on the entire substrate, and therefore will cover the beam, and the exposed portions of the recess under the beam. Only the portions of the stack on top of the beam are the operative portions, hence a photolithographic process is used to either wet etch or dry etch out the portions of the stack that cover the rest of the substrate other than the portion 1414 on the beam 1412, as shown in Figure 14E. Typically, the beam can be made anywhere from 0.2 micron to 20 microns thick; the length of the beam can range from 2 micron to several hundred microns, and the width of the beam can range from 2 micron to several microns. These parameters depend on the mechanical properties of the substrate material used to create the beam, and on the sensitivity required. The beam can

be designed to either have "standoff" from the substrate, or can be a free standing structure, with the bottom of the substrate completely etched out.

Although the invention has been described in detail with reference to the preferred embodiments thereof, those skilled in the art will appreciate that various substitutions and modifications can be made to the examples described herein while remaining within the spirit and scope of the invention as defined in the appended claims.